Short Communication

A model for the wear of brittle solids under fixed abrasive conditions

B. R. LAWN*

Institute for Materials Research, National Bureau of Standards, Washington, D. C. 20234 (U.S.A.)

Other than that the wear *mechanism* involves some microfracturing, and the wear *rate* is remarkably high, relatively little is known about the abrasion of highly brittle solids [1, 2]; this despite intense current interest in the machining and finishing of brittle surfaces within the ceramics engineering industry [3]. However, with the advent of "indentation fracture mechanics" a new approach has become available for investigating a wide range of small-scale cracking phenomena [4]. The purpose of the present note is to use this approach to construct an explicit model of the wear process in brittle solids, for the simple case of a "fixed" abrasive medium ("two-body" process) in which the grit particles are "ideally sharp".
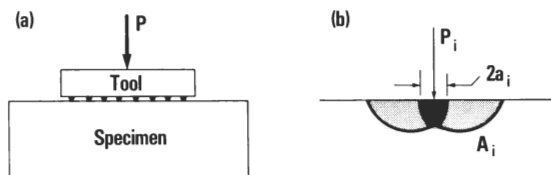

Fig. 1. Cross-sectional views of "fixed" abrasion process. (a) Macroscopic view: total load P bears on specimen *via* abrasive grit particles bonded to tool. (b) Microscopic view: i th particle experiences load P_i, and leaves in its wake a deformation track, width $2a_i$, from which lateral vents propagate to form chip, section area A_i. All particles translate across specimen surface with velocity v_0.

A schematic representation of the wear mechanism is given in Fig. 1. Macroscopically, one measures the wear rate $\dot{V} = dV/dt$ (V = volume removed) appropriate to a specified total load P and velocity v_0 for the abrasive medium relative to the specimen. Microscopically, attention focusses on the individual chip-removal mechanism, characterized by an "indenter" load P_i and velocity v_0 (all "indenters" traverse the specimen with the same velocity in the two-body configuration). The idea is to start with a mechanical description

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*On study leave, from School of Physics, University of New South Wales, Kensington, N.S.W. 2033 (Australia)

of the removal process for the i th indenter, and thence to sum over all such i events to predict the macroscopic behavior.

Resort is made to observations in "model" brittle solids (notably glass) of the fracture patterns beneath standard sharp indenters (e.g. cones, pyramids) [5, 6], to build up the following picture. Consider the sliding particle i to produce a "plastic" deformation track of width $2a_i$. Then, for geometrically similar impressions, the mean indentation pressure at any instant of contact may be identified with the material hardness [7],

$$p_i = P_i/\alpha\pi a_i^2 \approx H, \tag{1}$$

where α is a factor determined by indenter geometry. Upon *unloading*, residual stresses, associated with incompatibility between deformation zone and surrounding elastic matrix, initiate and propagate lateral, chip-forming cracks (so-called lateral vents; other cracks form on *loading*, but these extend straight downward, and play only a secondary role in chipping). In this view, the size of the prospective chip is determined by the configuration of the hardness impression, so the chip area may be written

$$A_i = \eta\, a_i^2, \tag{2}$$

where η is a linear scaling factor. The volume of material removed by the indenting particle in traversing through a distance Δl in an interval of time Δt is $\Delta V_i = A_i\Delta l$, whence, from eqns. (1) and (2),

$$\dot{V}_i = \Delta V_i/\Delta t = A_i\Delta l/\Delta t = (\eta v_0/\alpha\pi H)P_i. \tag{3}$$

A straightforward summation operation now gives the macroscopic wear rate;

$$\dot{V} = \sum_{i=1}^{N} \dot{V}_i = (\eta v_0/\alpha\pi H)\sum_{i=1}^{N} P_i = \eta v_0 P/\alpha\pi H. \tag{4}$$

This equation may be rearranged,

$$\dot{V}/v_0 P = \eta/\alpha\pi H, \tag{5}$$

such that the left and right sides conveniently represent macroscopic and microscopic parameters respectively*. It would thus appear possible to pre-determine the abrasive wear rate of brittle ceramics simply from quantities measured in standard hardness testing procedures.

Some data from soda-lime glass illustrate the principle. Taking $H \approx 1.0 \times 10^{10}$ Nm^{-2} ("dynamic" hardness) [8], $\alpha \approx 1$ (conical particles), $\eta \approx 1$, we predict $\eta/\alpha\pi H \approx 3 \times 10^{-11}$ m^2 N^{-1} as the wear rate. This compares with $\dot{V}/v_0 P \approx 1 \times 10^{-11}$ m^2 N^{-1} measured under test conditions in which chipping is pronounced (namely, spherical specimens on an alumina grinding block pre-ground with 45 μm diamond paste, decyl alcohol environment, at $P = 10$ N, $v_0 = 1$ ms^{-1}) [9].

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*A term equivalent to that on the left of eqn. (5), $\Delta V/P\Delta l$, is often used as an alternative expression of the macroscopic wear rate.

There are some interesting implications associated with the present model:

(i) The calculated wear rate is independent of the (apparent) area of contact between work tool and specimen, and also of the number and size of indenting particles. Thus, all arbitrariness and complication of a statistical analysis is avoided. Physically, this arises because of the essential "linearity" of the fixed-abrasive wear mechanism: the chip volume is proportional to the load on the indenting particle, so that the total volume removed does not depend on the way in which the total load is distributed.

(ii) The analysis tacitly assumes that the intensity of the residual stress field about the deformation track is sufficiently high to drive the chip-forming cracks to the surface. The indication from indentation fracture mechanics studies [10] is that the extent of micro-cracking relative to the size of the deformation zone diminishes with decreasing load. Thus we might anticipate a brittle-to-ductile, chipping-to-ploughing transition in wear mechanism at low abrasion loads, small particle sizes, with an attendant fall in wear rate to a value more typical of non-brittle solids [1]. Again, it has been assumed that geometrical similarity is preserved in the indentation fracture process. In practice, initially sharp particles tend to become "blunt" (either by fragmentation or by clogging with debris), and intersections tend to occur between neighboring tracks, as abrasion proceeds; these effects will further reduce the wear rate.

(iii) Most significantly, the wear rate under ideal chipping conditions is uniquely determined by the material *hardness*; by controlling the *scale* of the crack pattern behind the indenting particle, the "plasticity" properties of the material assume a key role in the abrasion process. However, hardness is a rate-dependent quantity which can change markedly with the conditions of testing, *e.g.* environment, load rate (sliding velocity), etc. [8, 11]. This bears strongly on the correlations between a wide range of chemo-mechanical properties (*e.g.* machining, drilling, grinding) and the hardness of brittle materials reported by Westwood and co-workers [12]. While the present model may provide a sound basis for interpreting chemo-mechanical phenomena, it needs to be emphasised that correlations of this type can be truly meaningful only if the hardness values are measured under conditions pertinent to the macroscopic situation.

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